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GPO PRICE $ ______

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Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

FACILITY FORM 602

N68-13579 (ACCESSION NUMBER)

45 (PAGES)

CR-91510 (NASA CR OR TMX OR AD NUMBER)

(THRU)

1 (CODE)

29 (CATEGORY)

UNIVERSITY OF MINNESOTA

THE OBSERVATION OF 10-50 KEV SOLAR FLARE X-RAYS BY THE OGO SATELLITES AND THEIR CORRELATION WITH SOLAR RADIO AND ENERGETIC PARTICLE EMISSION

by

R. L. Arnoldy, S. R. Kane
and J. R. Winckler

School of Physics and Astronomy
University of Minnesota
Minneapolis, Minnesota

Technical Report CR-107

September, 1967

This paper presented at International Astronomical Union Symposium No. 35
on the Structure and Development of Solar Active Regions

September 4-8, 1967
Budapest, Hungary

ABSTRACT

More than 70 cases have been observed of energetic solar flare x-ray bursts by large ionization chambers on the OGO satellites in space. The ionization chambers have an energy range between 10 and 50 Kev for x-rays and are also sensitive to solar protons and electrons. A study has been made of the x-ray microwave relationship and it is found that the total energy released in the form of x-rays between 10 and 50 Kev is approximately proportional to the peak or total energy simultaneously released in the form of microwave emission. For a given burst the rise time, decay time and total duration are similar for the 10-50 Kev x-rays and the 3 or 10 cm radio emission. Roughly exponential decay phases are observed for both emissions with time constants between 1 and 10 minutes. All 3 or 10 cm radio bursts with peak intensity greater than 80 solar flux units are accompanied by an x-ray burst greater than 3×10^{-7} ergs cm^{-2} sec^{-1} peak intensity. The probability of detecting such x-ray events is low unless the radio spectrum extends into the centimetric range of wavelengths. The best correlation between cm-λ and energetic x-rays is observed for the first event in a flare. Subsequent structure and second bursts may not correspond even when the radio emission is rich in the microwave component. A very good correlation exists between the occurrence of large SID events (importance - 3) and energetic x-rays. The overall correlation for importance 1, 2 and 3 is 55%. Almost 90% of the x-ray bursts were accompanied by known SID events. The mechanism for the energetic x-rays is shown to be bremsstrahlung probably of fast electrons on a cooler plasma. The mechanism for the radio emission is basically uncertain. However, if it is assumed to be synchrotron radiation then a relationship is developed

between density and magnetic field which meets the observed quantitative results. One finds, on the average, that 5×10^{-54} joules m^{-2} $(CPS)^{-1}$ of microwave energy at earth are required per electron at the sun to provide the radio emission for the various events.

A strong correlation between interplanetary solar flare electrons observed by satellite and x-ray bursts are shown to exist. This correlation is weak for solar proton events. One may infer a strong propagation asymmetry for solar flare electrons along the spiral interplanetary magnetic field.

I. INTRODUCTION

Since September 1964 ionization chambers flown in space have detected numerous solar flare x-ray bursts in the energy range from 10 to 50 Kev originating in solar flare disturbances. In the present paper we shall present the most recent summary of these observed events and discuss their relationship with the microwave solar radio bursts and with the observations of energetic electrons and protons ejected into space by the same flares. The central object of such a study is to reach a better understanding of the solar flare processes and the nature of the instability which generates flares but, in particular, to understand the processes which gave rise to suprathermal particles so frequently observed from flares.

The x-rays are detected by ionization chambers carried for long periods of time outside the magnetosphere by the OGO-I and OGO-III satellites. Details of the instrumentation and previous work on this program have been summarized in several publications (Kane et al, 1966; Arnoldy et al, 1967a; Arnoldy et al, 1967b). The range of energies covered by the present experiments is similar to, but in general somewhat less than, the x-ray events detected previously by balloons flown near the top of the atmosphere (Peterson and Winckler, 1959; Winckler et al, 1961; Vette and Casal, 1961; Anderson and Winckler, 1962; Hofmann and Winckler, 1963). Several summaries of this very energetic bremsstrahlung emission from flares and their relationship to the radio and optical features are available, based on the older results (Winckler, 1963; Friedman, 1964; Kindu, 1965). In a general sense the energetic flare x-rays of energy above 10 Kev appear as bursts of duration between 1 and 20 minutes in very good time simultaneity with the "explosive" phase of flares (Moreton, 1964). Previously, the observations of these energetic x-rays were made by chance on high altitude balloons carrying ion chambers or scintillation counters. These early experiments detected only the most energetic quanta from the flare due to the atmospheric absorption above the balloons. These rather exceptional events have given rise to considerable speculation about processes which could produce energetic quanta such as the inverse Compton process (Acton, 1964; Shklovsky, 1964; Schklovskii, 1965; Zheleznyakov, 1965), the synchrotron process (Stein and Ney, 1963), or nuclear processes giving gamma rays. The results of the present study show that flares of all sizes from Class 1S to Class 3B emit such energetic x-rays and that their origin is probably bremsstrahlung following the suprathermal heating of electrons in the magnetic plasma medium in the solar active region. Our recent investigation (Arnoldy et al, 1967b) has shown that the x-ray bursts are well-correlated with the direct observation immediately afterward in space of energetic electrons greater than 40 Kev energy which may well come from the same source (Lin and Anderson, 1967). In this paper and the previous related accounts we also have found evidence that the acceleration of solar flare protons which are now widely observed in interplanetary space or at the earth may arise from a process disjoint from that responsible for the x-ray-electron emission.

II. DISCUSSION OF THE OGO EXPERIMENTS

The x-rays were detected with an 18 cm diameter aluminum wall ionization chamber filled with argon gas at 3.5 atmospheres pressure. Identical instruments were provided for the OGO-I (launched September, 1964) and the OGO-III (launched June, 1966) satellites both of which continue to give data. Details of the instrumentation are given in our previous publications (Kane et al, 1966; Arnoldy et al, 1967b).

The ion chamber response has a lower limit of 10 Kev, has a maximum response between 20 and 30 Kev and an effective upper limit between 50 and 100 Kev depending on the type of spectrum characteristic of the x-rays. In this paper the ion chamber rates are given in the various figures in terms of a standardized arbitrary rate designated as normalized pulses/sec x 10^3 (NPPS x 10^3). The response characteristics and factors for converting the chamber rate to absolute energy flux are given in Table 1. For the analysis in this paper, we have assumed a rather steep exponential type x-ray spectrum with E_0 = 7 Kev. The threshold sensitivity of the chamber for x-rays is 3 x 10^{-7} ergs cm^{-2} sec^{-1}. The chamber responds also to protons above 12 Mev, to electrons above 700 Kev, and frequently detects particle events in space closely following the x-ray bursts from the same flare.

Recently some solar x-ray events have been detected simultaneously by both OGO-I and III. Figure 1 shows such an example and also delineates the orbital positions of the two satellites with respect to the magnetospheric structure. Such simultaneous events make the identification of the x-ray increase completely certain and help to distinguish spurious cases due to electron bursts associated with the magnetosphere. The example shown in Figure 1 is also interesting because of the sharp burst at 1712 UT and the rather smooth maximum at 1730. The close agreement of the two ion chambers measuring the same event shows that the calibrations used were correct and that no drift has occurred in the calibration of the OGO-I instrument over a period of two and a half years.

III. CORRELATION OF X-RAY AND RADIO BURSTS

We have continued the study of OGO satellite data reported in the earlier papers and have approximately doubled the number of events by extending the analysis through December 1966. We shall now summarize the results of this total analysis and give examples to illustrate the principal findings.

A. Both the peak intensity and the total energy released in the form of x-rays between 10 and 50 Kev is approximately proportional to the peak or total energy simultaneously released in the form of microwave emission in either the 3 or 10 cm range of frequencies. The correlation of the integrated x-ray and radio emission for about 60 events is shown in Figure 2. The integral has been carried out over the "first" radio or x-ray burst for the flare as it seems always true that the first x-ray burst and the first microwave emission correspond extremely well, but subsequent increases ("second bursts") may or may not correlate well. These facts will be brought out more clearly by the examples below. The correlation of peak intensities is shown in Figure 3. The reasonable linear relationship between both integrated and peak x-ray and microwave intensity strongly suggests a common basic energy source for the two phenomena or even that the same electrons may be emitting both the x-rays and radio waves. This proportionality will permit us to draw conclusions about the radio process based on an assumed mechanism and on the known characteristics of bremsstrahlung emission (see the discussion).

There is evidence that the newer events, corresponding to a later period in the increasing solar cycle show more x-ray emission relative to the radio event (see open points in Figures 2 and 3).

This is not caused by any change in apparatus calibrations (see Figure 1).

A result similar to this has been found by Kawabata (1966) for the relation between some soft x-ray events observed by the satellite SR-1 and cm-λ emission.

B. For a given flare burst the rise time, decay time and total duration are similar for the 10-50 Kev x-rays and for the 3 or 10 cm radio emission. Such a similar time history is not characteristic of extremely soft x-rays from flares which resemble more closely the optical emissions; or, on the other hand, for extremely energetic quanta which may completely disappear after the first impulse of the flare.

A large event on 30 March 1966 is illustrated in Figure 4. Another large event on 7 July 1966 is shown in Figure 5 where the results of Cline et al (1967) for x-rays $>$ 80 Kev also measured on OGO-III are shown for comparison. A solar proton event from the same flare begins on the ion chamber before the x-ray decay is complete.

C. If one plots the decay phase of the radio and 10-50 Kev x-ray bursts frequently this appears to be roughly exponential and to have similar time constants for the two emissions. These time constants vary between 1 and 10 minutes. Frequently, however, after the first impulsive maximum the radio emission has much structure especially for the large complex type events which is only weakly or not at all followed in the x-ray emission. In a qualitative sense similarities in fine structure are observed during the early part of the events and many differences develop later.

The decay of a complex event is shown in Figure 6. This event illustrates the steady character of the x-ray decrease, and the large fluctuations during the radio decay.

D: Statistically, all 3 or 10 cm radio bursts with peak intensity greater than 80 solar flux units are accompanied by an x-ray burst greater than 3×10^{-7} ergs cm^{-2} sec^{-1} peak intensity in the range 10-50 Kev. In the inverse sense there exist a small number of x-ray events constituting a few percent of the total as an upper limit which are not accompanied by a radio burst. These conclusions apply to the initial impulsive part of the flare event. Second bursts or complex structure later in an event vary considerably in the degree of correlation.

E. The probability of detecting an x-ray event associated with a radio burst under the energy and sensitivity limits of this investigation is low unless the radio spectrum extends into the centimetric range of wavelengths. This feature is characteristic both of the initial burst and of subsequent bursts for a given flare. This spectral feature is illustrated by Figures 7 and 8 for events on 5 June 1965 and 9 December 1966. In each case the "second" radio maximum seen, for example, on 10 cm has a spectrum predominantly in the deca-metric or metric range and is not accompanied by an x-ray increase. One may suppose that the metric emission is not compatible in general with a plasma density sufficient to produce a detectable bremsstrahlung output. This may be due to the greater coronal heights of emission during this phase. In Figure 9 (4 October 1965) is shown an event in which the initial burst is largely metric, and no x-rays are observed. In this case a solar proton event ensues. The proton acceleration process may thus be of a different character than that giving the suprathermal "tail" of thermal electrons.

F. The best correlation is observed for the first event in a flare between cm-λ and energetic x-ray emission. Even some detailed structure may correspond well at the start of the outburst. Subsequent structure and "second" bursts may not correspond, even when the radio emission is rich in the microwave component.

A striking example observed by balloon equipment on 20 July 1961 (Hofmann and Winckler, 1963; see also Bruzek, 1964; Ellison et al, 1961) is shown in Figure 10. Here the 3 and 10 cm emission during the "second" maximum at 1615 UT was very strong, but no large flux of energetic quanta appeared. Solar protons from the "flash" at 1550 UT had already reached the balloon by this time. Two other examples of the inverse effect in Figure 11 (18 March 1966) and Figure 12 (31 March 1966) show cases of long duration - post burst type radio increases with little or no indication of a special correspondence to a well defined "second" x-ray maximum. Such cases where electrons emit microwaves but no bremsstrahlung, or bremsstrahlung but no microwaves may be attributed to variation of height, plasma density, magnetic field strength or other parameters which can inhibit some processes of emission while allowing others.

G. A very good correlation exists between the occurrence of large SID events (importance - 3) and the 10-50 Kev range of x-rays measured here as can be seen from Table 2. Here all the SID events which occurred during the OGO observation period between September 1964 and December 1966 are considered. From Table 2 it may be noted that the correlation increases from 50 to 80 percent with the increase in the importance of the SWF events from 1 to 3. The overall correlation is about 55 percent.

The inverse correlation (x-ray - SID, 3 cm or 10 cm radio bursts) is shown in Table 3. Here the relationship is presented for two periods, viz. September, 1964 - June, 1966 (period A) and July, 1966 - December, 1966 (period B). During period A the x-ray - SID and x-ray - radio correlations are almost 100 percent. However, during period B there are about 20 percent more x-ray bursts than the SID events or radio bursts. This may suggest a gain in the hard x-rays relative to either soft x-rays (SWF) or radio emission as the solar cycle progresses. This conclusion has limited statistical validity, however.

IV. INTERPRETIVE REMARKS ABOUT THE X-RAY RADIO RELATIONSHIP

Because of the very close morphological relation between the x-ray production and the centimetric range of radio emission it is very plausible to search for a model or to propose a situation in which both types of electromagnetic emission come from a common source. In the paper of Peterson and Winckler (1959) the source of the x-rays was assumed to be bremsstrahlung from energetic electrons in an energy range around 500 Kev. The radio emission was then assumed to be by the synchrotron process from the same electrons. This lead to the difficulty that about 10^4 times too much radio emission was expected compared to the observed. Takakura (private communication, 1963); (1966) examined the situation and proposed that the region of emission was different for the x-rays and the radio bursts and was able to adjust the radio power at the same time retaining the concept that the same energy region of electrons was responsible for both emissions.

The many examples given in this paper have been presented purposely to show the complex character of the situation. Early in the flare event there appears to be a very close relationship between x-rays and microwaves and as time progresses the radio emission assumes a time structure frequently not closely related to the smoothly disappearing x-ray burst. There are many variations of this behavior, however, We are thus faced with an event-by-event description of various phenomena which might include surges of material to high altitude as well as emission at great depths. For example, observations of a flare event on 20 November 1960 which occurred some 23° behind the solar west limb produced both microwave emission and x-rays causing a SWF. The analysis of Ellison et al (1961) showed that these emissions came from a region 60,000 km above the photosphere. It will thus be difficult or impossible to form a single model applicable to all events. However, for the initial part of the events where the correlation is very strong between x-rays and microwaves, it may be possible.

In our previous paper (Arnoldy et al, 1967b) we attempted to visualize the simplest possible situation that was consistent with the experimental facts and did not assume special kinds of processes not specifically dictated by the results. We recall the approximate proportionality between the x-ray and radio emission as shown above and the similarity in duration and decay rate of the two types of emission. Two possible cases are considered: (a) that the characteristic time constant is determined entirely by the time variation of the basic energy source itself with all other time constants associated with specific processes (for example, synchrotron emission) being shorter than this. In case (b) the source is impulsive but a single dominant electron decay process determines the time constant for both the x-ray and radio emission. This time constant could be that required for the suprathermal electrons responsible for the bremsstrahlung to disappear by collision loss in the plasma. We consider that the same plasma region and probably the same electrons are producing both the x-ray and radio emission. The plasma is entrained in a magnetic field above the solar active center. These fields must play a major role in the acceleration of particles and in the emission and propagation of radio frequency energy. For any quantitative calculations the emission process must be made specific. Our model assumes that very hot energetic or suprathermal electrons lose energy predominantly by collisions with a much cooler plasma. This point of view has also been suggested by Elwert (1961). Neither the present measurements, nor the original measurements of Peterson and Winckler (1959) can provide exact energy discrimination. Thus a re-interpretation of the 20 March 1958 event of Peterson and Winckler, made by Chubb et al (1966) in terms of an exponential spectrum with E_0 about 60 Kev is probably acceptable. However, balloon scintillation counter measurements by Anderson and Winckler (1962) showed directly the presence of photons >150 Kev energy, and Cline et al (1967) have shown flare bremsstrahlung spectra at 100 Kev. We do not consider plausible the concept that there exists a complete plasma at an enormously elevated temperature and that one is justified in using the thermal bremsstrahlung approach for computing the x-ray emission power for such events. The thermal bremsstrahlung approach with very high temperatues has been consistently proposed by the NRL group (for example, see Chubb et al, 1966). It is true that the concept of temperature is often applied to one component of a medium, for example electron energies are frequently given in terms of electron temperature if the energy distribution appears to be exponential. However, one might expect that using the concept of temperature would imply that the medium is close to a thermodynamic equilibrium condition and that one is therefore justified in applying this same temperature to compute many types of processes such as, for example, the distribution of ionization states, spectral emission, etc. There appears to be no evidence at all that the temperatures deduced from other means in flare regions reach the enormous values of 10^8° which one is forced to assume for the electronic bremsstrahlung emission seen as hard x-rays. Optical measurements (de Jager, 1959) frequently show 10,000 to 20,000 degrees as typical. We therefore favor the point of view that the electron heating in the flare region is highly non-equilibrium and may be associated with such phenomena as magneto-hydrodynamic waves and that there exists an energy distribution characteristic of a much lower temperature with a large suprathermal tail.

We now consider a quantitative estimate of the bremsstrahlung emission. In case (a) where the time behavior of the event is determined entirely by the energy source, the collision lifetime is very short. One can use the thick target bremsstrahlung equation given by Koch and Motz (1959) for non-relativistic electrons

$$\varepsilon = 5 \times 10^{-4} \, Z \frac{E_K}{m_o c} \tag{1}$$

where ε is the efficiency defined as (total energy radiated)/(total beam energy), E_K the kinetic energy, and Z the atomic number of the target. Considering 100 Kev electrons for a large event such as 30 March 1966 or 7 July 1966 a beam energy of 3×10^{30} ergs is required which is equivalent to 2×10^{32} electrons. If we consider case (b) where an impulsive injection of 100 Kev electrons is assumed the collision loss determines the decay of the event (from one to ten minutes) and gives density estimates of 3×10^{10} atoms cm^{-3} by 3×10^{9} atoms cm^{-3} for the lifetime range of one to ten minutes respectively. The bremsstrahlung power is calculated also from the results of Koch and Motz (1959) valid for electron energies of 10-100 Kev incident on neutral hydrogen. Quantitatively, the relationship reduces to the following, where P is the number of photons between 10 and 50 Kev per cm^2 per sec measured at the earth, and N_H and N_e are respectively the densities of hydrogen and energetic electrons situated in the volume V.

$$P = 3 \times 10^{-43} N_H N_e V \text{ photons cm}^{-2} \text{ sec}^{-1} \qquad (2)$$

If N_H can be estimated from observed event lifetimes, and if P is measured, then equation (2) may be used to compute the total number of electrons, $N_e V$. Again for a large x-ray event the value of P is 1.5×10^4 and from the observed mean lifetime of 300 seconds N_H is estimated to be 5×10^9 cm^{-3}. For this density 10^{37} electrons are required in the impulsive injection process, i.e. essentially the same number as calculated under assumption (a).

Considering the radio emission this is often attributed to synchrotron radiation. Although this is certainly a plausible mechanism the detailed measurements of polarization and other factors do not exclude a thermal source accompanied by propagation effects which produce polarization. In fact, Kundu (1965) suggests that the microwave burst events may frequently be a mixture of thermal and synchrotron emission. Considering a large event such as 30 March 1966 and 7 July 1966 the microwave energy received at earth at 3 cm was approximately 6×10^{-17} joules m^{-2} $(CPS)^{-1}$. Following our basic assumption that the same electrons are responsible for both processes, about 5×10^{-54} joules m^{-2} $(CPS)^{-1}$ of microwave energy at earth are required per electron at the sun on the average. This number will be approximately the same for all events as long as the proportionality between x-ray and microwave emission is valid. The large difference in size from event to event is thus principally due to the difference in number of electrons in the source.

For the purposes of discussion we have assumed that the microwave energy is from the synchrotron emission of electrons of intermediate energy. Following the work of Takakura (1960) for electrons of intermediate energy and assuming 50 and 100 Kev energies one can calculate the total power radiated by an electron in uniform circular motion averaged over 4π solid angle. For a given frequency and electron energy the power radiated per electron depends only on the magnetic field B. On the other hand, for bremsstrahlung the power radiated per electron depends only on the density of hydrogen. Thus, as shown in Figure 13 one achieves a relation between density and magnetic field for the two chosen discrete energies such that the observed proportionality between energetic x-ray and 3 cm emission is satisfied. In case (b) (impulsive injection by source) it becomes apparent that the 3 cm emission is occurring close to the 20th harmonic for an acceptable magnetic field. The emissivity at this harmonic is several orders of magnitude below that near the gyrofrequency and we consider this to be a very improbable physical situation. However, if one allows higher densities and very short electron lifetimes as in case (a) (where the duration of the event is controlled by the source) then the permissible magnetic field is much higher and the harmonic is reduced to a plausible value. In practice one would, of course, wish to use a continuous spectrum of electron energies such as the computation of Takakura (1966). But with the very short lifetime due to collisions and a re-generation continuously during the event by the source one achieves with reasonable magnetic field strengths the low stored flux of electrons required to agree with the observed radio emission. Thus the original difficulty in the calculation of Peterson and Winckler is resolved.

Figure 13 shows also the density corresponding to the plasma frequency for the ionized component at several temperatures and also on the X-axis with an extended scale the magnetic field corresponding to the gyrofrequency. The radio emission must occur within the rectangle limited by these lines.

The relationship shown in Figure 13 between density and magnetic field strength corresponding to the discrete energies 50 Kev and 100 Kev may possibly define some direct physical situation in the flare region. We show in Figure 14 a mean curve for 75 Kev and a family of curves for different values of the ratio, β, of thermal energy to magnetic energy for a chosen tamperature of 7500°K. One might suppose that during an active time the magnetic field above the sunspot regions would be carrying a large plasma density and that possibly the β-value might tend to be constant in different portions of the field.
However, the empirical curve for 75 Kev spans several orders of magnitude variation in β as shown in Figure 14. If, indeed, there is any direct physical significance to this curve then it implies that the magnetic field is more heavily loaded with plasma for high field strengths and very lightly loaded in the upper corona where the field strengths are small.

V. ENERGETIC PARTICLE RELATIONSHIPS

The OGO ionization chamber can detect solar particle events as well as x-ray bursts and frequently shows intensity increases following a flare which are clearly due to charged particles from the sun. The ionization chamber is very sensitive to protons and can detect a flux of 0.01 protons cm^{-2} sec^{-1} of energy greater than 12 Mev. The chamber also is sensitive to electrons greater than 700 Kev but in principle cannot distinguish the type of particle responsible for a given increase. An example of a small particle event following the 5 June 1965 x-ray event discussed previously (see Figure 7) is shown in Figure 15. The event begins at 1900 UT and reaches a maximum at 2100 UT. Interpreted as protons, this implies 0.07 protons cm^{-2} sec^{-1} but this increase could also presumably be due to electrons greater than 700 Kev. In fact, this event produced an identified electron increase in both the Mariner IV and IMP I satellites (Van Allen and Krimigis, 1965; Lin and Anderson, 1967) of energies greater than 40 Kev.

A very large x-ray event on 28 August 1966 followed by a solar proton event which eventually became very large is shown in Figure 16. In this case the x-ray increase was roll modulated by the spinning spacecraft when the ion chamber was eclipsed by the body of the spacecraft. One notes the lack of roll modulation for the particle event. The maximum in solar particle intensity was reached at 2100 UT with an ion chamber rate of 15000 NPPS x 10^3. One notes the lack of correlation between the large radio maximum at 1605 and the x-ray intensity.

The release into space of electrons above 40 Kev energy associated with solar flares has now been observed on many occasions by the IMP spacecraft (Lin and Anderson, 1967). It is possible to use IMP data to determine which OGO particle events did not contain electrons and presumably were due to solar protons. Also both the IMP electron events and the proton events can be correlated with the occurrence of energetic x-ray bursts and microwave emission. A complete summary with tables for the period September, 1964 through June, 1966 has been given in our previous paper (Arnoldy et al, 1967b). These correlations may be summarized as follows:

A. Of 8 proton events observed by the ionization chamber but not detected as electron events on IMP satellite, 7 were not associated with solar flare energetic x-rays. An example of such an event is given in Figure 9. It appears, therefore, that the production of solar protons is not necessarily closely correlated with the processes producing electrons and energetic bremsstrahlung.

B. Eight large electron events detected when the OGO and IMP spacecraft were simultaneously operating in interplanetary space had associated x-ray bursts. The remaining 4 electron events were very small and were not recorded by OGO as x-rays nor was there microwave emission. This rather good correlation of x-ray bursts with interplanetary electron events suggests that the flare electrons that leak out into interplanetary space might be from the same supra-thermal source as those responsible for the energetic x-rays. For the 5 June 1965 event the observed number of electrons measured directly in space above 40 Kev can be provided by the leakage into interplanetary space from the flare region of about 0.1% of the number of electrons required to produce the corresponding x-ray event.

C. The reverse correlation where one begins with known OGO x-ray bursts and compares IMP data for interplanetary electrons shows

12 events with no interplanetary electrons. It is striking that all 12 were produced by flares near or east of central meridian. It is very reasonable to assume that the absence of electrons in these cases is due to a propagation asymmetry between the sun and the earth similar to that previously observed for high energy solar protons caused by the spiral interplanetary magnetic field.

D. It is generally found that very large flares such as 7 July 1966 or 28 August 1966 produce all types of energetic solar phenomena simultaneously. X-rays, microwave emission, interplanetary electrons and solar protons are all observed.

ACKNOWLEDGMENTS

We are indebted to the radio observatories of Penn State, Nancay, Nera, Toyokawa and Ottawa who have furnished many original records for this study and to Dorothy Trotter, World Data Center A for Solar Activity, for lists of outstanding occurrences. Preliminary use has been made of optical data prepared for us by Helen W. Dodson-Prince and E. Ruth Hederman of McMath-Hulbert Observatory. We are also grateful to Dr. M. Pick of Meudon Observatory for important assistance with solar radio and optical interpretation, to R. Lin and Professor K. A. Anderson of the University of California, Berkeley for assisting with the IMP electron correlations, and to Mr. Karl Pfitzer for major assistance with OGO data reduction. Data analysis was assisted by a Guggenheim Fellowship to one of the authors (J. R. Winckler) for study at the Observatoire de Meudon. This work has been supported by the National Aeronautics and Space Administration under Contract No. NAS5-2071.

FIGURE CAPTIONS

1. A solar flare x-ray increase observed simultaneously by the ion chamber on OGO-I and OGO-III satellites. This x-ray burst has a sharp preliminary peak at 1712 UT and a broad maximum centered at 1730. A satisfactory 10 cm radio correlation exists.
2. Correlation of integrated x-ray and integrated radio flux for the observed events. The integral has been carried out over the first event in a flare occurrence. A roughly linear relation exists, but the events later in the solar cycle between July 1966 and December 1966 appear relatively more rich in x-ray emission than the earlier events.
3. Correlation of peak x-ray and radio fluxes. The tendency for a solar cycle effect can also be traced in this figure.
4. Comparison of x-ray intensities (lower) and 3 and 10 cm radio emission (above) for a large complex flare event.
5. The response of the OGO ion chamber for 10-50 Kev x-rays and the > 80 Kev x-rays also detected on the OGO satellite (Cline et al, 1967) compared to microwave emission. Note the much shorter lifetime for the more energetic bremsstrahlung.
6. The decay of a complex event showing similar trends for x-rays and 3 cm radio emission.
7. An example of a rather detailed x-ray-radio correspondence for the first event in the flare beginning at 1807 but showing the lack of observable x-rays corresponding to the predominantly metric event beginning at 1821.

8. Another event similar to Figure 7 showing the lack of correspondence when the radio spectrum is predominantly metric rather than centimetric.

9. A flare event with low intensity of cm-λ emission but with appreciable metric band energy. Note the beginning of a solar proton event at 1030 UT and the absence of an x-ray burst.

10. An example of a limb event observed by balloon equipment in which the first increase produces a solar x-ray event but the second large microwave increase has no detectable x-rays. A solar proton increase from this west limb flare has begun by 1612. (See Hofmann and Winckler, 1963).

11. Complex event showing a sizeable second x-ray maximum with weak corresponding radio emission.

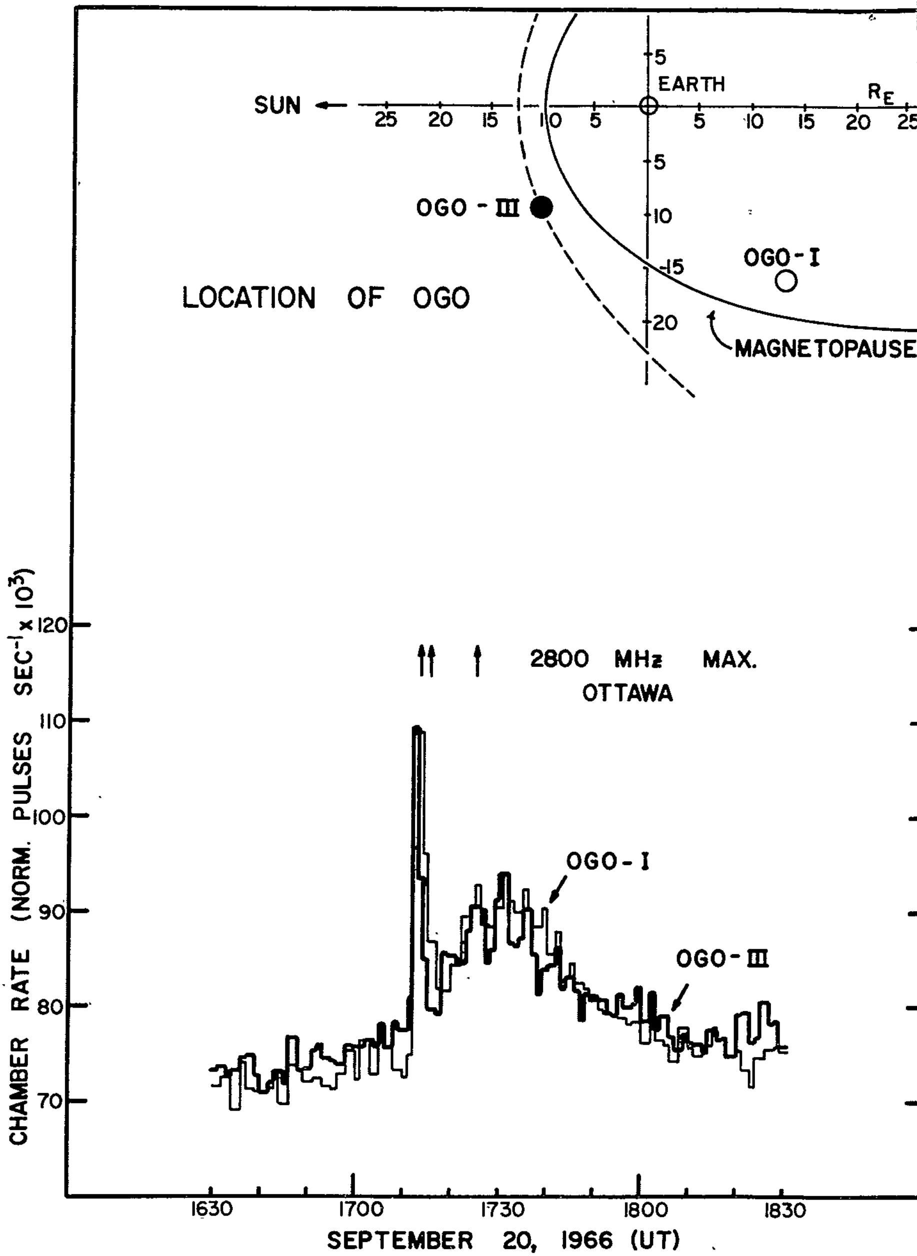
12. A large double x-ray event corresponding to a long duration microwave increase. No detectable radio event corresponds to the second x-ray maximum at 1927 UT.

13. The density required to give the observed bremsstrahlung power per electron expressed as a function of the magnetic field required to give the observed radio emission at 10,000 MHz by the synchrotron process. The relation is shown for discrete energies of 50 Kev and 100 Kev. Any point along the curves will satisfy the observed proportionality between the microwave and x-ray emission under the assumptions presented in the text. The densities at which the plasma frequency of the medium is equal to 10,000 MHz is indicated for various temperatures. The magnetic field strength which gives an electron gyrofrequency of 10,000 MHz is also shown.

14. An examination of the hypothesis that the magnetic field-density curve (for mean energy 75 Kev) physically represents the thermal to magnetic energy relationship in the plasma.

15. A small x-ray event showing the ensuing solar particle event observed by the ionization chamber. These particles are not specifically identified by the OGO ion chamber but may be solar protons. Solar electrons were observed by several experiments (see text) and correspond to this particle increase.

16. The great event on 28 August 1966. Note the almost complete roll modulation of the x-ray burst with the 96 second roll period of OGO-III. This roll modulation is not present in the solar particle increase beginning at 1550 UT. Only the initial features of the complex radio burst are reflected in the x-ray profile.


SUN
25 20 15 10 5
EARTH
5 10 15 20 25
R_E
5
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OGO - III
OGO - I
LOCATION OF OGO
MAGNETOPAUSE
CHAMBER RATE (NORM. PULSES SEC⁻¹ x 10³)
120
110
100
90
80
70
2800 MHz MAX.
OTTAWA
OGO - I
OGO - III
1630
1700
1730
1800
1830
SEPTEMBER 20, 1966 (UT)

FIGURE 1

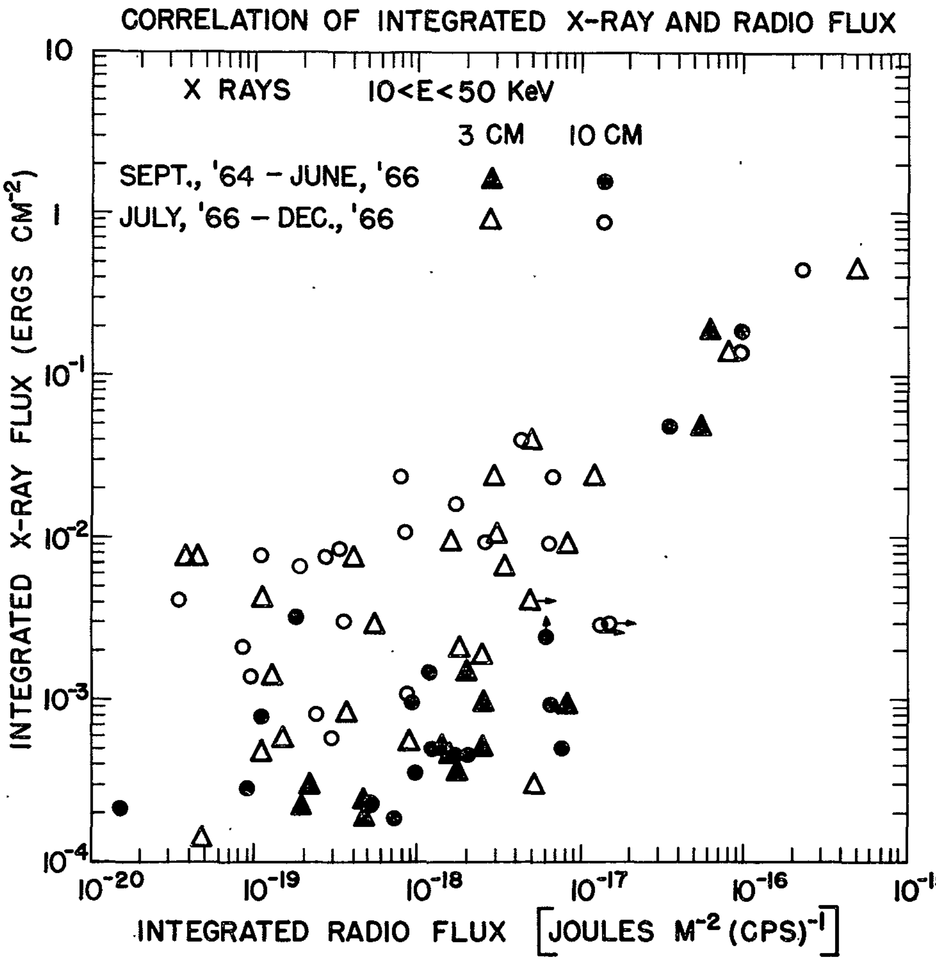

CORRELATION OF INTEGRATED X-RAY AND RADIO FLUX
X RAYS 10<E<50 KeV
3 CM 10 CM
SEPT., '64 – JUNE, '66
JULY, '66 – DEC., '66
INTEGRATED X-RAY FLUX (ERGS CM^{-2})
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
10^{-15}
INTEGRATED RADIO FLUX [JOULES M^{-2} (CPS)$^{-1}$]

FIGURE 2

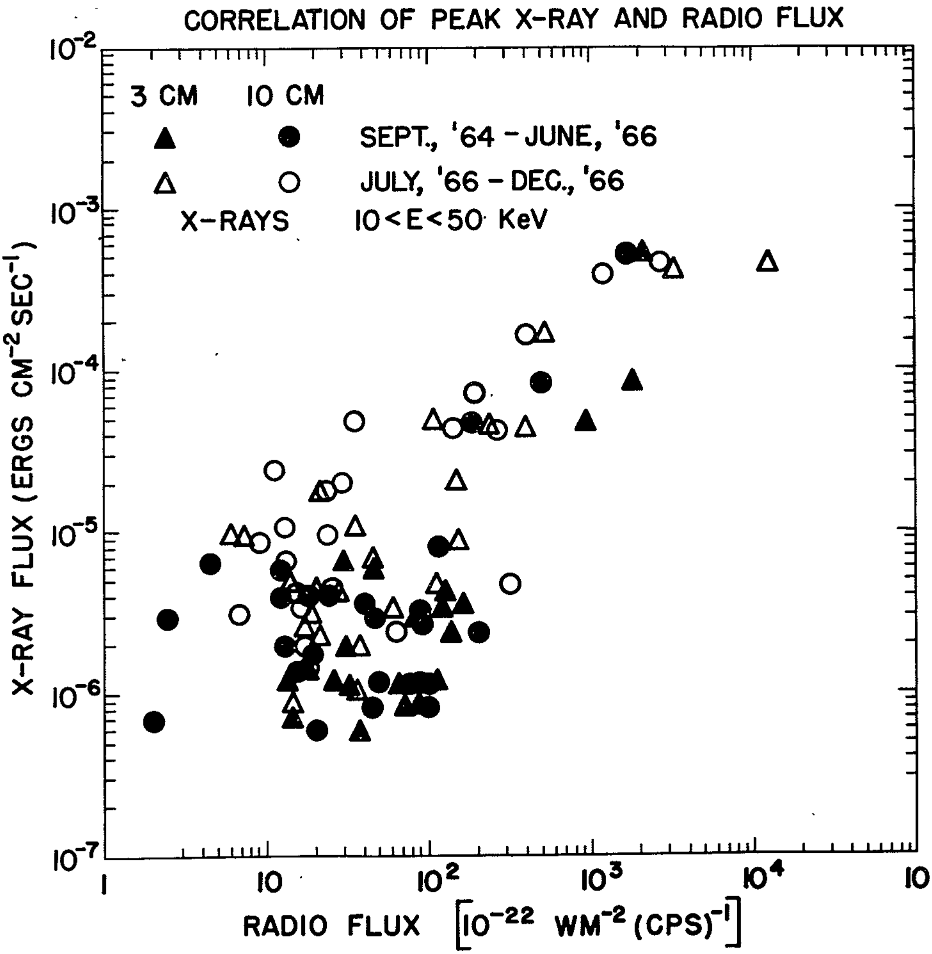

CORRELATION OF PEAK X-RAY AND RADIO FLUX
3 CM
10 CM
SEPT., '64 - JUNE, '66
JULY, '66 - DEC., '66
X-RAYS
10<E<50 KeV
X-RAY FLUX (ERGS CM^{-2} SEC^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
10
10^2
10^3
10^4
10^5
RADIO FLUX [10^{-22} WM^{-2} (CPS)$^{-1}$]

FIGURE 3

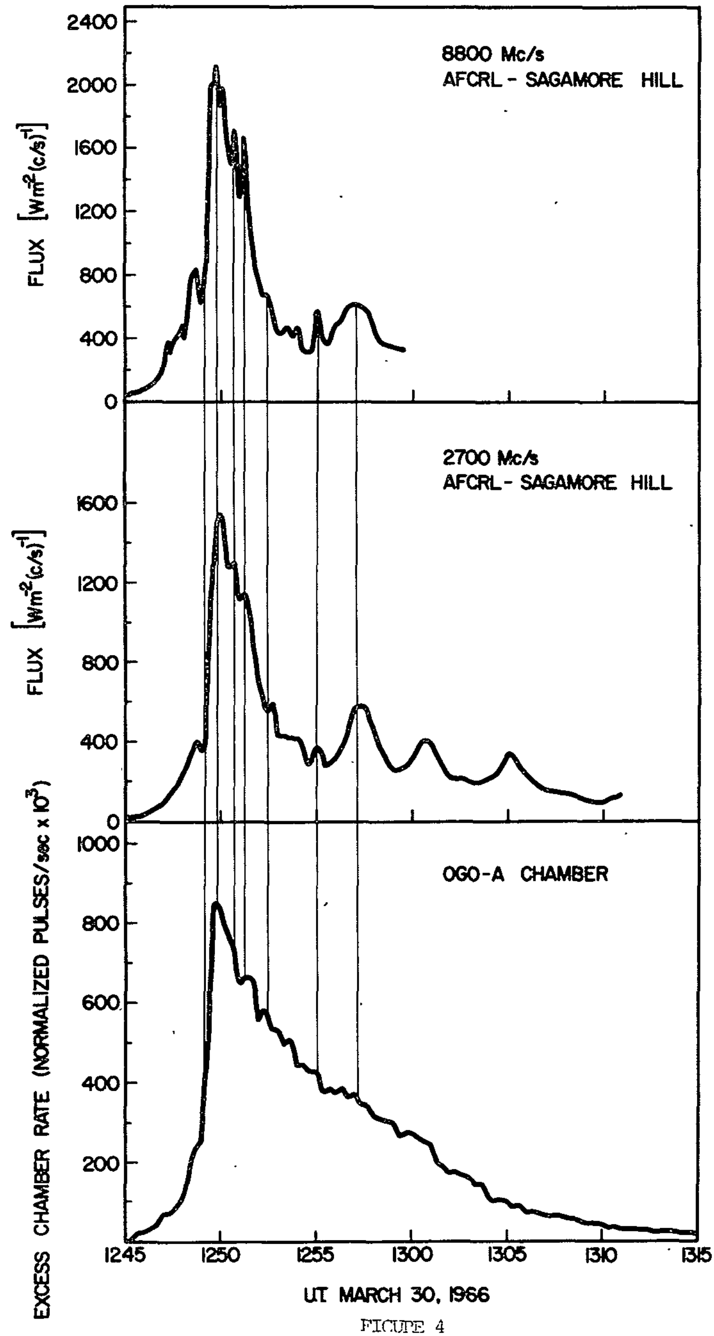
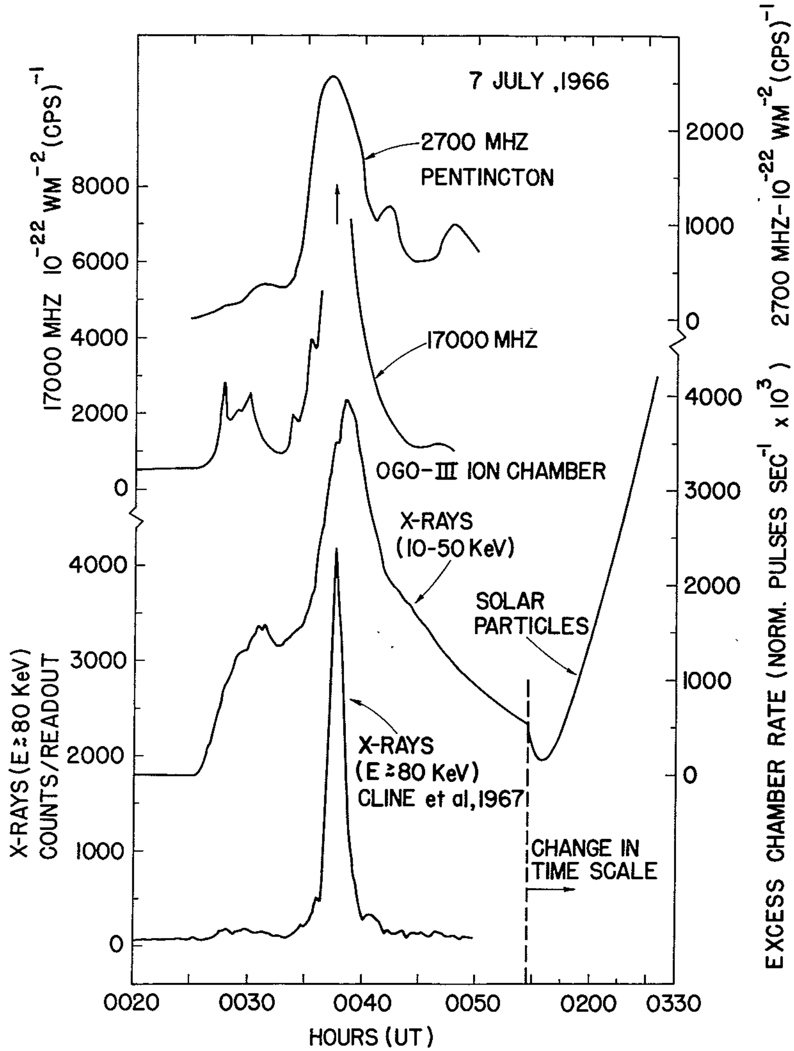

8800 Mc/s
AFCRL - SAGAMORE HILL
2700 Mc/s
AFCRL - SAGAMORE HILL
OGO-A CHAMBER
FLUX [Wm^-2(c/s)^-1]
FLUX [Wm^-2(c/s)^-1]
EXCESS CHAMBER RATE (NORMALIZED PULSES/sec x 10^3)
2400
2000
1600
1200
800
400
0
1600
1200
800
400
0
1000
800
600
400
200
1245
1250
1255
1300
1305
1310
1315
UT MARCH 30, 1966

FIGURE 4



7 JULY ,1966
2700 MHZ PENTINCTON
17000 MHZ
OGO-III ION CHAMBER
X-RAYS (10-50 KeV)
SOLAR PARTICLES
X-RAYS (E ≥ 80 KeV) CLINE et al, 1967
CHANGE IN TIME SCALE
17000 MHZ 10^{-22} WM^{-2} (CPS)$^{-1}$
X-RAYS (E ≥ 80 KeV) COUNTS/READOUT
2700 MHZ-10^{-22} WM^{-2} (CPS)$^{-1}$
EXCESS CHAMBER RATE (NORM. PULSES SEC^{-1} x 10^3)
0020
0030
0040
0050
0200
0330
HOURS (UT)

FIGURE 5

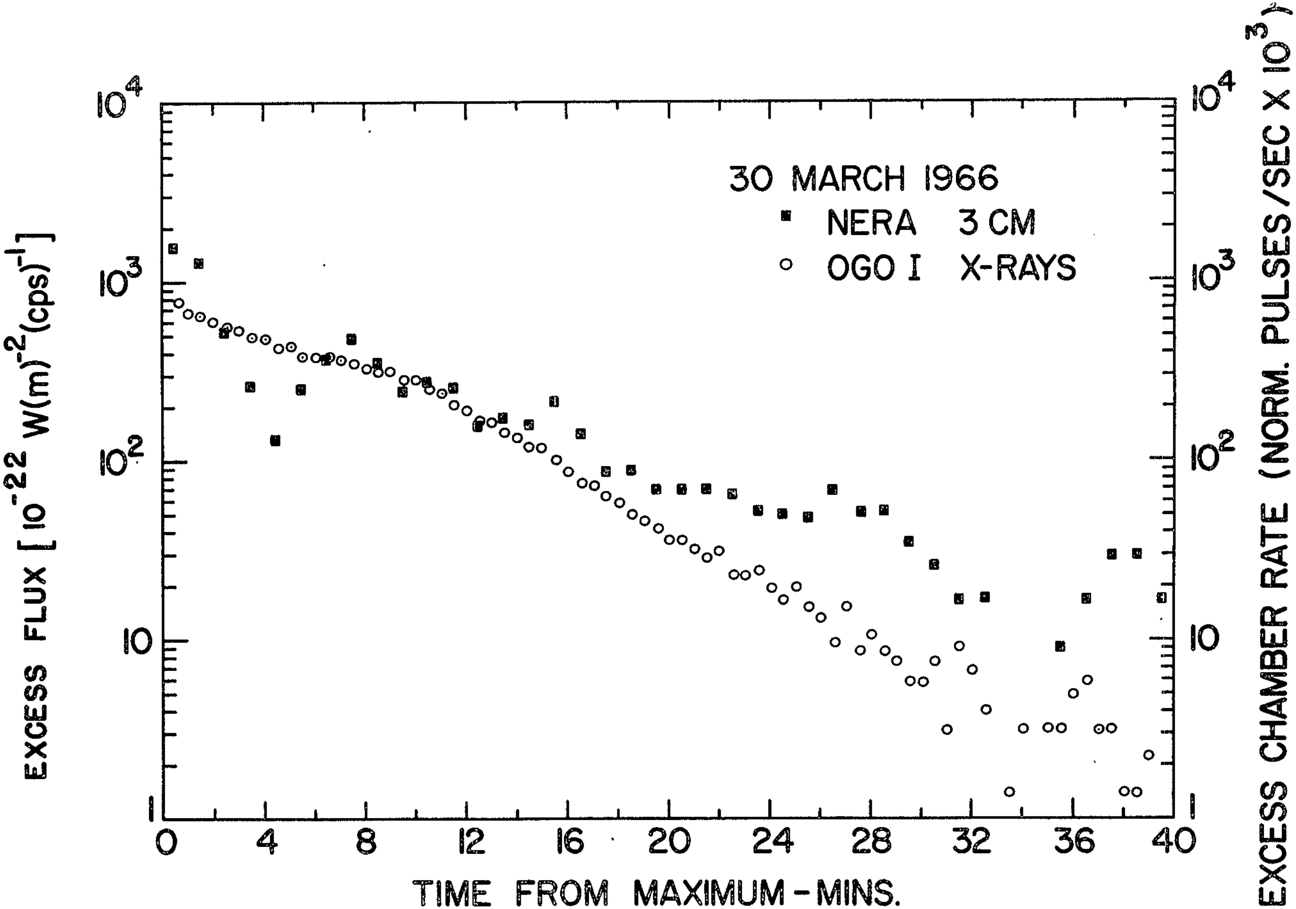

30 MARCH 1966
NERA 3 CM
OGO I X-RAYS
EXCESS FLUX [10^{-22} W(m)$^{-2}$(cps)$^{-1}$]
EXCESS CHAMBER RATE (NORM. PULSES/SEC X 10^3)
TIME FROM MAXIMUM - MINS.
10^4
10^3
10^2
10
1
0
4
8
12
16
20
24
28
32
36
40

FIGURE 6

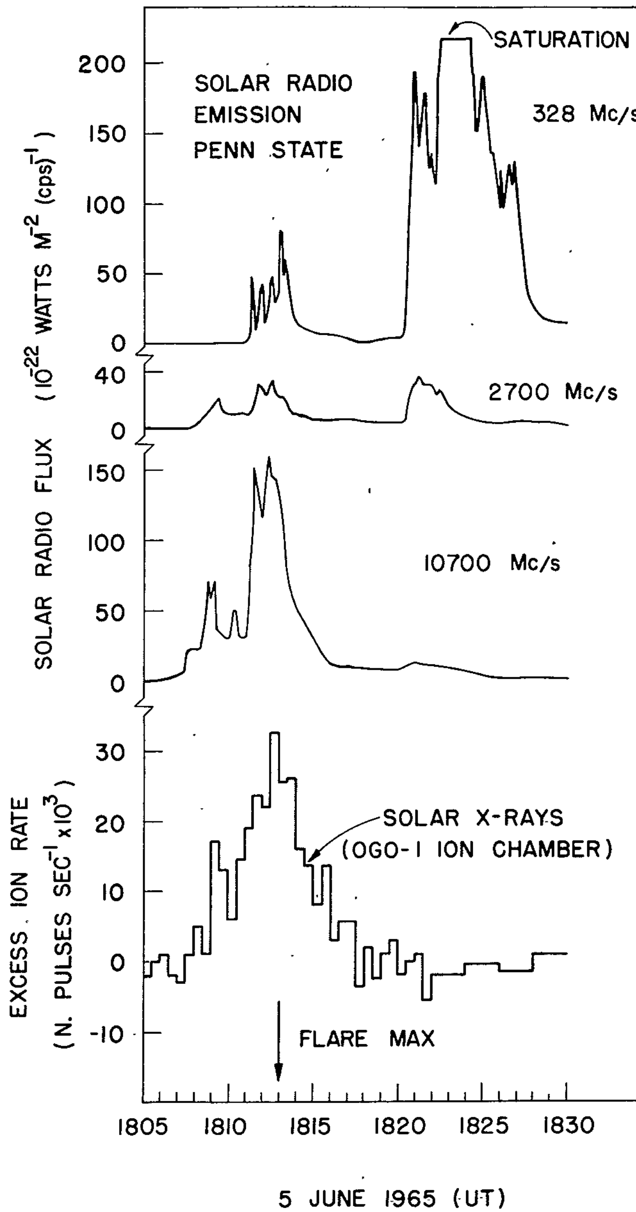

SATURATION
SOLAR RADIO
EMISSION
PENN STATE
328 Mc/s
2700 Mc/s
10700 Mc/s
SOLAR RADIO FLUX (10^{-22} WATTS M^{-2} $(cps)^{-1}$)
200
150
100
50
0
40
0
150
100
50
0
SOLAR X-RAYS
(OGO-I ION CHAMBER)
EXCESS ION RATE
(N. PULSES SEC^{-1} $x10^{3}$)
30
20
10
0
-10
FLARE MAX
1805
1810
1815
1820
1825
1830
5 JUNE 1965 (UT)

FIGURE 7

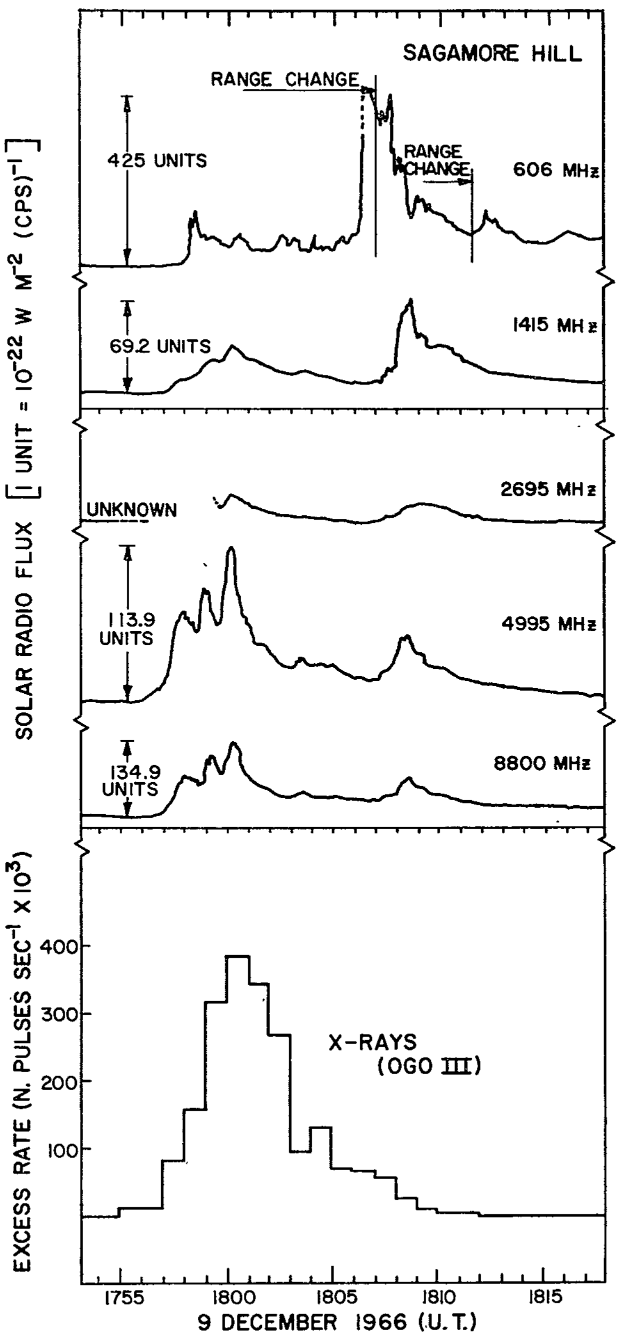

SAGAMORE HILL
RANGE CHANGE
RANGE CHANGE
425 UNITS
606 MHz
69.2 UNITS
1415 MHz
2695 MHz
UNKNOWN
113.9 UNITS
4995 MHz
134.9 UNITS
8800 MHz
SOLAR RADIO FLUX [1 UNIT = 10^-22 W M^-2 (CPS)^-1]
EXCESS RATE (N. PULSES SEC^-1 X 10^3)
400
300
200
100
X-RAYS
(OGO III)
1755
1800
1805
1810
1815
9 DECEMBER 1966 (U.T.)

FIGURE 8

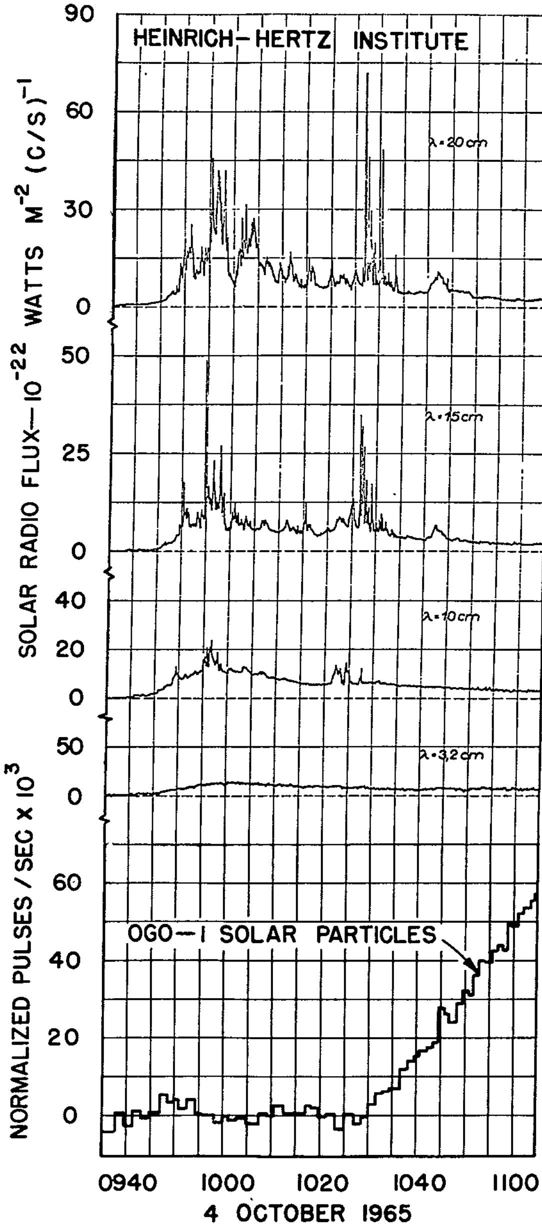

HEINRICH-HERTZ INSTITUTE
SOLAR RADIO FLUX—10^{-22} WATTS M^{-2} $(C/S)^{-1}$
90
60
30
0
50
25
0
40
20
0
50
0
λ=20cm
λ=15cm
λ=10cm
λ=3,2cm
NORMALIZED PULSES / SEC x 10^3
60
40
20
0
OGO—I SOLAR PARTICLES
0940
1000
1020
1040
1100
4 OCTOBER 1965

FIGURE 9

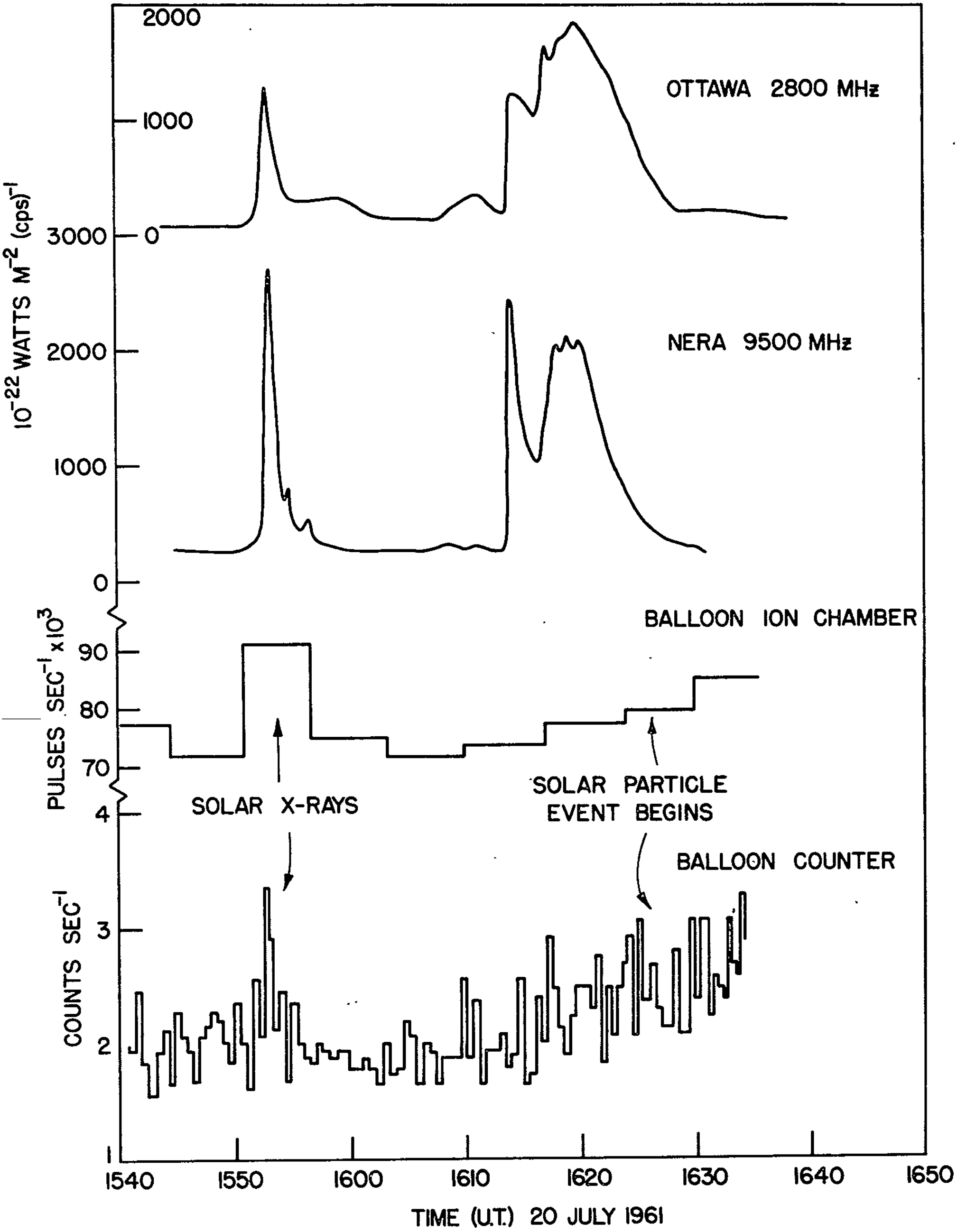

2000
1000
0
OTTAWA 2800 MHz
3000
2000
1000
0
10^{-22} WATTS M^{-2} (cps)$^{-1}$
NERA 9500 MHz
BALLOON ION CHAMBER
90
80
70
PULSES $SEC^{-1} \times 10^{3}$
SOLAR X-RAYS
SOLAR PARTICLE EVENT BEGINS
BALLOON COUNTER
4
3
2
1
COUNTS SEC^{-1}
1540
1550
1600
1610
1620
1630
1640
1650
TIME (U.T.) 20 JULY 1961

FIGURE 10

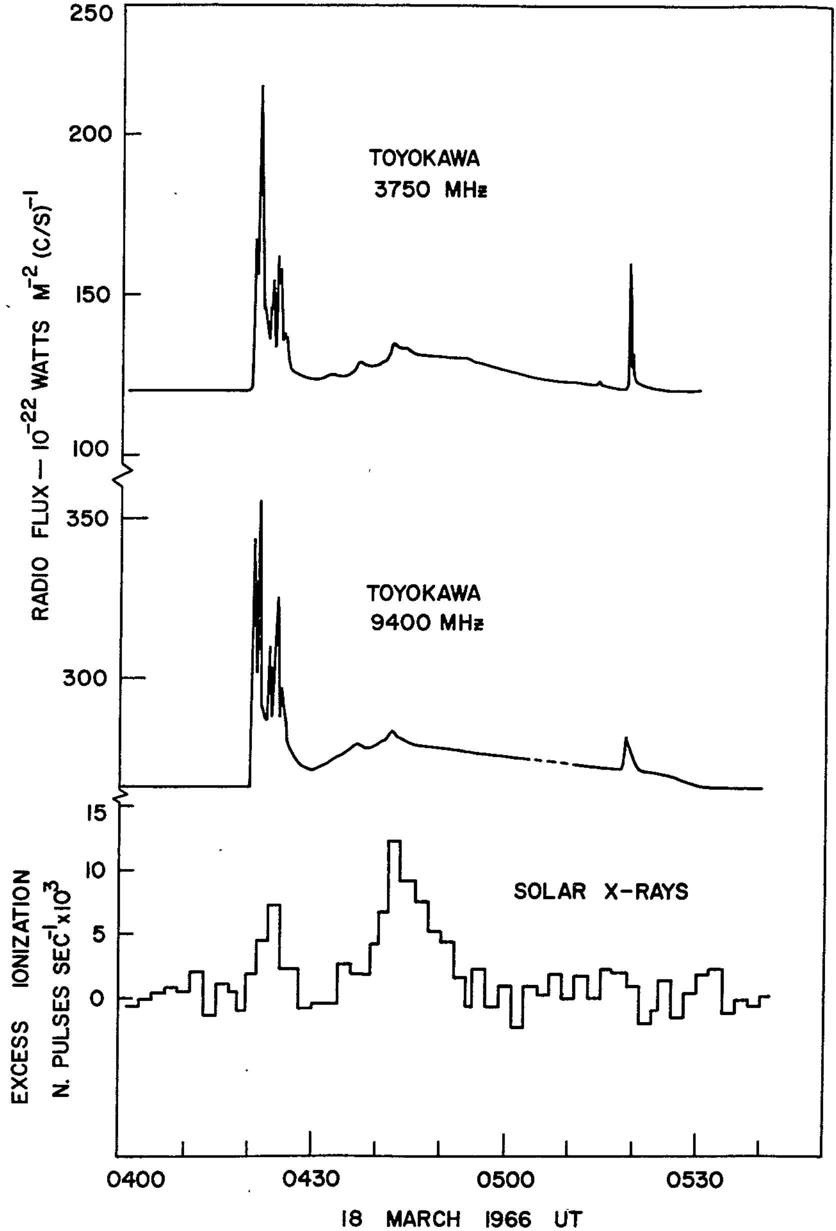
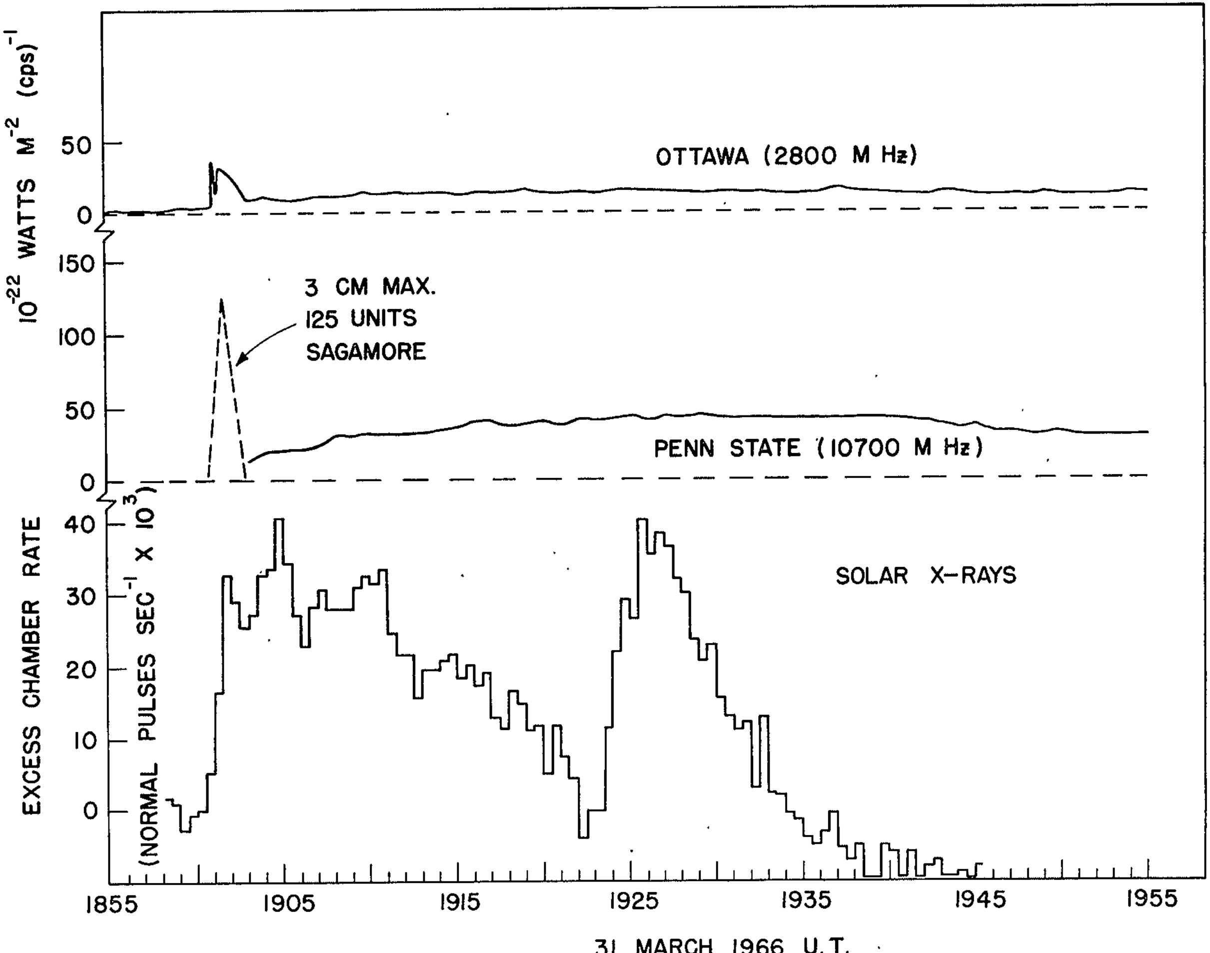

250
200
150
100
350
300
15
10
5
0
TOYOKAWA
3750 MHz
TOYOKAWA
9400 MHz
SOLAR X-RAYS
RADIO FLUX — 10^{-22} WATTS M^{-2} $(C/S)^{-1}$
EXCESS IONIZATION
N. PULSES $SEC^{-1} \times 10^{3}$
0400
0430
0500
0530
18 MARCH 1966 UT

FIGURE 11



10^{-22} WATTS M^{-2} $(cps)^{-1}$
50
0
OTTAWA (2800 M Hz)
150
100
50
0
3 CM MAX.
125 UNITS
SAGAMORE
PENN STATE (10700 M Hz)
EXCESS CHAMBER RATE
(NORMAL PULSES SEC^{-1} X 10^3)
40
30
20
10
0
SOLAR X-RAYS
1855
1905
1915
1925
1935
1945
1955
31 MARCH 1966 U.T.

FIGURE 12

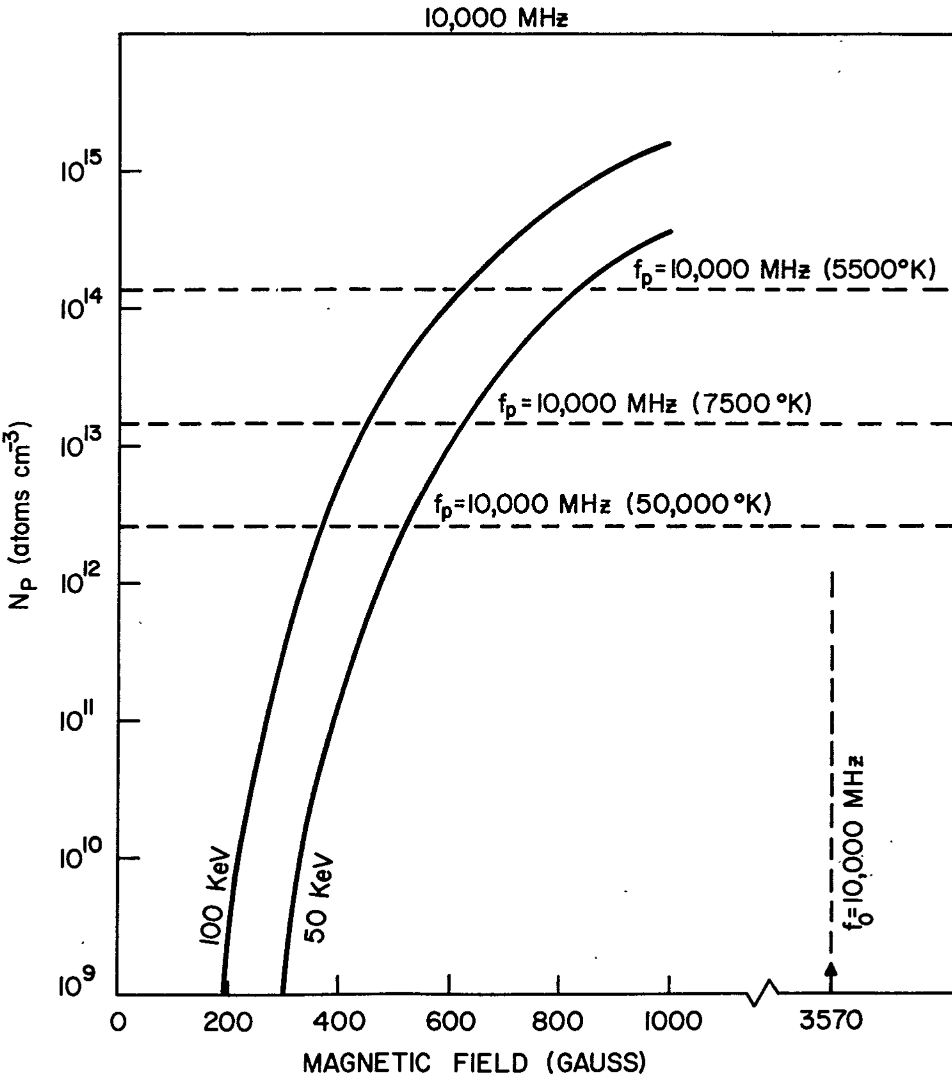

10,000 MHz
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
N_P (atoms cm^{-3})
f_p=10,000 MHz (5500°K)
f_p=10,000 MHz (7500 °K)
f_p=10,000 MHz (50,000 °K)
100 KeV
50 KeV
f_o=10,000 MHz
0
200
400
600
800
1000
3570
MAGNETIC FIELD (GAUSS)

FIGURE 13

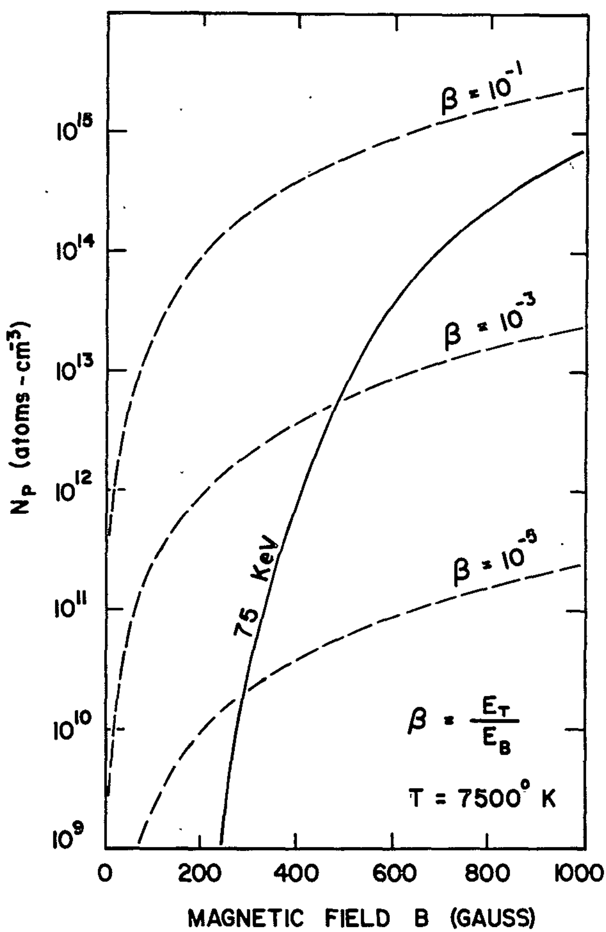

$\beta = 10^{-1}$
$\beta = 10^{-3}$
$\beta = 10^{-5}$
75 KeV
$\beta = \frac{E_T}{E_B}$
T = 7500° K
N_P (atoms - cm^{-3})
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
0
200
400
600
800
1000
MAGNETIC FIELD B (GAUSS)

FIGURE 14

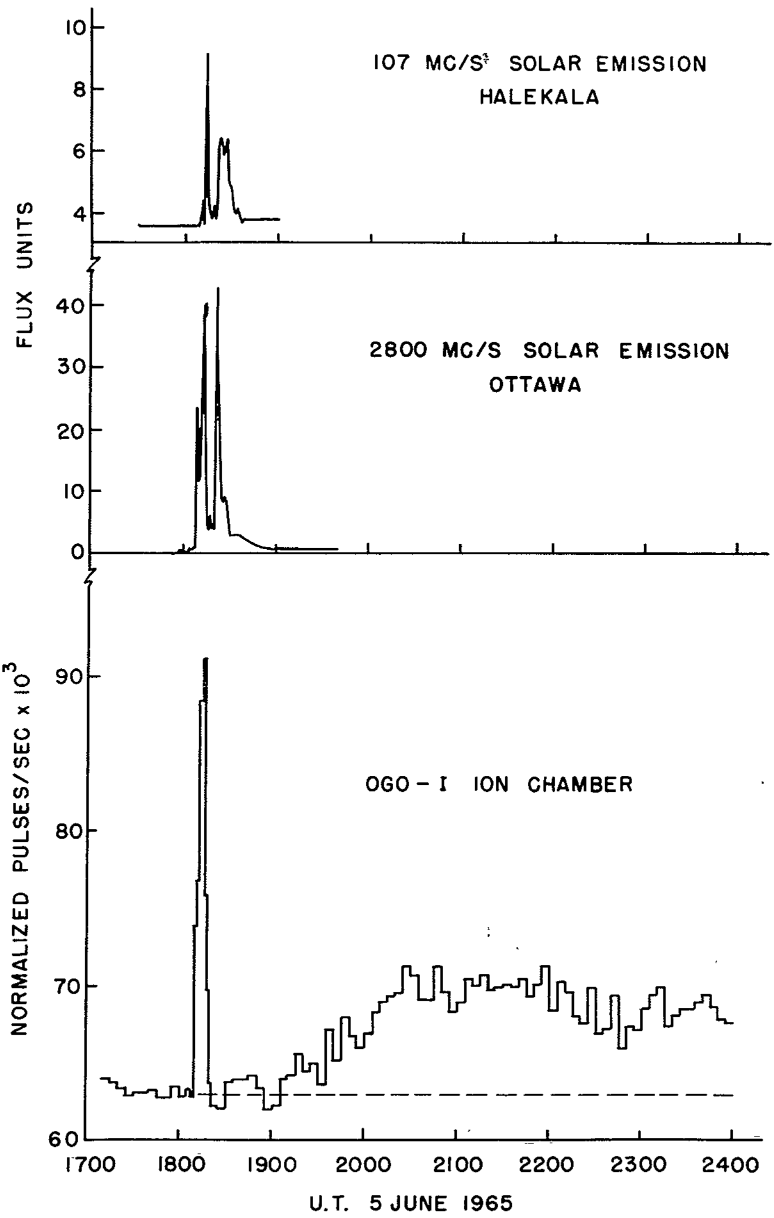

107 MC/S SOLAR EMISSION
HALEKALA
FLUX UNITS
10
8
6
4
2800 MC/S SOLAR EMISSION
OTTAWA
40
30
20
10
0
OGO - I ION CHAMBER
NORMALIZED PULSES/SEC x 10^3
90
80
70
60
1700
1800
1900
2000
2100
2200
2300
2400
U.T. 5 JUNE 1965

FIGURE 15

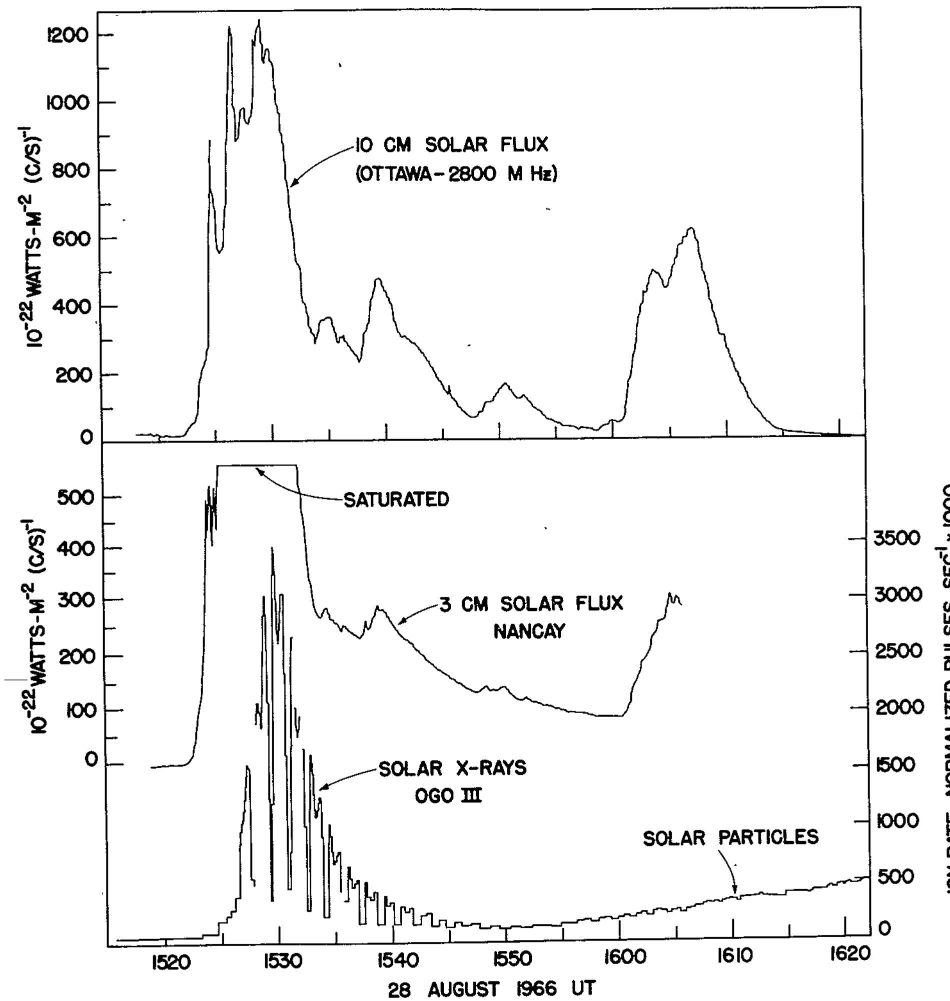

1200
1000
800
600
400
200
0
10^{-22} WATTS-M^{-2} (C/S)$^{-1}$
10 CM SOLAR FLUX
(OTTAWA - 2800 M Hz)
500
400
300
200
100
0
10^{-22} WATTS-M^{-2} (C/S)$^{-1}$
SATURATED
3 CM SOLAR FLUX
NANCAY
SOLAR X-RAYS
OGO III
SOLAR PARTICLES
3500
3000
2500
2000
1500
1000
500
0
ION RATE - NORMALIZED PULSES SEC^{-1} x 1000
1520
1530
1540
1550
1600
1610
1620
28 AUGUST 1966 UT

FIGURE 16

Table 1

ION CHAMBER RESPONSE

Primary X-Ray Spectrum $dN/dE = e^{-E/E_0}$ photons cm^{-2} sec^{-1} Kev^{-1}

E_0 (Kev)	CHAMBER RATE (N. pulses sec^{-1} x 10^3)			TOTAL	INCIDENT ENERGY FLUX >10 Kev ergs cm^{-2} sec^{-1}	CONVERSION FACTOR $\frac{\text{ergs } cm^{-2} sec^{-1}}{\text{N. pulses } sec^{-1} \times 10^3}$
	10-16 Kev	16-106 Kev	106-150 Kev			
7	0.026	0.116	5.1×10^{-8}	0.142	1.7×10^{-8}	1.2×10^{-7}
20	0.106	1.16	1.8×10^{-3}	1.27	4.7×10^{-7}	3.7×10^{-7}
50	0.165	2.61	0.07	2.85	3.8×10^{-6}	1.3×10^{-6}

Table 2

SID - X-Ray Correlation

September, 1964 - December, 1966

SWF Importance	1	2	3
No. of SWF occurring during OGO observation periods	91	26	10
No. of correlated x-ray events detected by OGO	45	18	8

Table 3

$$\text{X-Ray} \;\text{--}\; \left\{\begin{array}{l}\text{SID}\\ \text{3 cm}\\ \text{10 cm}\end{array}\right. \;\text{Correlation}$$

Time Period	X-ray Bursts	CORRELATED EVENTS		
		SWF	3 cm or 10 cm	SWF and 3 cm or 10 cm
Sept., 1964- June, 1966	27	26	27	26
July, 1966- Dec., 1966	52	44	45	38
Total	82	70	72	64

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